



Thermo-economic optimization of secondary distribution network of low temperature district heating network under local conditions of South Korea

Park, Byung Sik; Imran, Muhammad; Hoon, Im-Yong ; Muhammad, Usman

Published in:
Applied Thermal Engineering

Link to article, DOI:
[10.1016/j.applthermaleng.2017.07.080](https://doi.org/10.1016/j.applthermaleng.2017.07.080)

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Park, B. S., Imran, M., Hoon, I-Y., & Muhammad, U. (2017). Thermo-economic optimization of secondary distribution network of low temperature district heating network under local conditions of South Korea. *Applied Thermal Engineering*, 126, 117-133. <https://doi.org/10.1016/j.applthermaleng.2017.07.080>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Thermo-economic optimization of secondary distribution network of low temperature district heating network under local conditions of South Korea

Byung-Sik Park¹, Muhammad Imran^{2,3,*}, Im-Yong Hoon¹, Muhammad Usman⁴

¹Energy Efficiency Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea

²Thermal Energy, Department of Mechanical Engineering, Technical University of Denmark, Akademivej, 2800, Kgs. Lyngby, Denmark

³Energy Engineering Department, School of Engineering, University of Management and Technology, C-II Johar Town Lahore, Pakistan

⁴Department of Mechanical Engineering, University of Engineering & Technology, Lahore, G.T Road, Lahore, 54890, Pakistan

*Corresponding Author: Muhammad Imran; Tel.: +92-345-5573234

Email: muhammadimran@umt.edu.pk

ABSTRACT

A secondary distribution network of a low temperature district heating system is designed and optimized for a residential apartment complex under the local conditions of South Korea in the TRNSYS simulation environment. The residential apartment complex is a typical example of Korean residential apartment. The Apartment complex has 15 floors, 4 apartments on each floor and each apartment has heating surface area of 85m^2 . The supply temperature of the hot water is reduced from 65°C to 45°C and the temperature difference between supply and return line is varied from 18°C to 27°C . The corresponding heat loss from secondary network, pumping power and area of domestic hot water heat exchanger unit for each supply temperature and temperature difference for required heating load of the apartment complex are calculated. Results indicate that when supply temperature is decreased from 65°C to 45°C , area of heat exchanger is increased by 68.2%, pumping power is also increased by 9.8% and heat loss is reduced by 15.6%. These results correspond to a temperature difference of 20°C , the standard temperature difference in South Korea residential heating system. Economic assessment of the secondary distribution network shows that the supply temperature of 55°C and 60°C are economically more feasible than 65°C and 45°C .

Keywords

District Heating; Optimization; 4th Generation District Heating; Secondary Network; TRNSYS; Low Temperature District Heating

Nomenclature

A	Area, (m ²)	Nu	Nusselt Number
b	Heat Exchanger Plate Spacing, (m)	P	Pressure, (Pa)
D	Diameter, (m)	Pr	Prandtl Number
DH	District Heating	Pco	Corrugated pitch, (m)
DHW	District Hot Water	Q	Heat Transfer Rate, (kWh)
D_h	Hydraulic Diameter, (m)	Re	Reynolds Number
$HPCD$	Horizontal Port Center Distance, (m)	SH	Space Heating
H_p	Pump Head, (m)	T	Temperature, (°C)
k	Thermal Conductivity, (W/m.K)	t	Thickness of Heat Exchanger Plate, (m)
L	Length, m	U	Overall Heat Transfer Coefficient, (W/m ² .K)
$LTDH$	Low Temperature District Heating	$VPCD$	Vertical Port Center Distance, (m)
$LMTD$	Log Mean Temperature Difference, (K)	V_{fr}	Flow rate, (m ³ /s)
\dot{m}	Mass Flow Rate, (kg/s)	W	Width of Heat Exchanger Plate, (m)
Greek Letters			
β	Chevron Angel, (Degree)	μ	Viscosity, (kg/s.m)
ρ	Density, (kg/m ³)	α	Convective Heat transfer Coefficient, (W/m ² .K)
γ	Specific Weight	η	Efficiency
Subscripts			
a	Ambient	p	Plate
d	Difference	r	Return
e	Effective	hx	Heat Exchanger
s	Supply	w	Water

Introduction

Compared to the conventional in house boiler heating system, district heating is convenient, environmental friendly, efficient, reliable, and ensure the energy security due to availability of a wide range of energy sources. District heating (DH) system has a development history of more than hundred years, which can be divided into four stages based on supply temperature and energy efficiency, as shown in Figure 1.

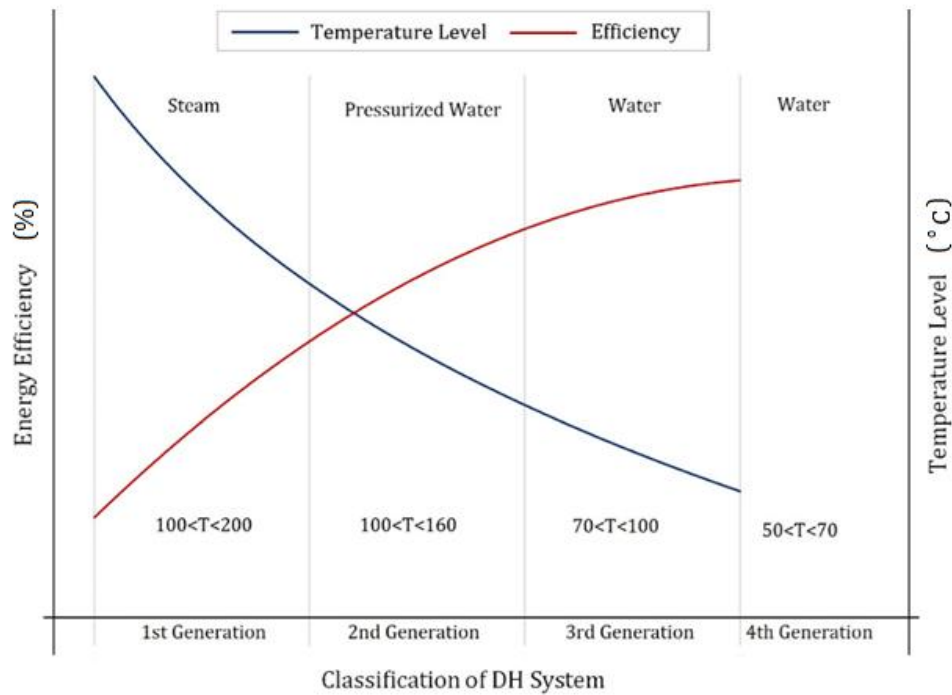


Figure1: Development of different heating system over the period and their performance [1]

Almost all the present DH systems in China, South Korea, Europe, USA and Canada are 3rd generation DH systems. A careful observation shows that the trend of DH system development was towards the low supply temperature, DH equipment optimization, flexible material, and prefabrication of DH in-house and substation units [2-3]. DH system will play an important role in the future renewable energy share, greenhouse gas free society and energy security. Therefore, the DH system must be further developed to reduce the heat losses, exploit the available renewable energy resources, and use the lower supply temperature [4-6]. Recently, the 4th generation DH system is introduced which uses lower distribution temperature, assembly-oriented components and more flexible pipe materials [7].

The low temperature DH system reduces network heat loss, improves quality match between heat supply and heat demand, reduces pipeline thermal stress, provides flexibility in the selection of pipe materials, reduces boiling risk, improves power-to-heat ratio in steam CHP plants, higher heat utilization from flue gas

condensation, higher coefficient of performances in heat pumps, higher utilization of low temperature sources, and reduces heat loss in thermal storage units [8-10]. The low temperature district heating is being successfully implemented in EU and other developed countries. Table 1 provides the list of the low temperature district heating projects and their operating conditions that have been successfully demonstrated and completed during the last fifteen years.

Table 1: List of successful low temperature district heating projects [11]

Name	T_s (°C)	T_r (°C)	T_a (°C)	Trench Length meter	Specific Heat Loss MJ/m	Heat Density MJ/m ²	Specific Heat Demand MJ/m ²	Heat Loss %
Kirsehir, Turkey	57	38	11	NA	255	NA	186	15
Lystrup, Denmark	52	34	8	767	134	46	191	20
Okotoks, Canada	39	31	4	1045	236	86	335	13
Halmstad, Sweden	70	38	7	470	356	67	187	12
Falkenberg, Sweden	78	44	7	342	125	89	122	16
Munich, Germany	59	33	10	1240	296	277	223	18
Slough, UK	51	34	11	165	96	71	152	28
Taastrup, Denmark	70	40	9	2743	255	NA	152	13

The literature review of these projects shows that the low temperature district heating is technically and economically feasible. The future development in district heating will follow the 4th generation DH system. It will result in an increase of the share of renewable energy in DH heat sources, reduce the environmental impact and improve the energy efficiency of DH system.

Selection of the appropriate heating and cooling system for a building can be successfully achieved by integrating energy efficiency with proper economic assessment. In this regard, the effect of design parameters and equipment sizing play major role [12]. A novel approach of combined low temperature water heating system is investigated by [13]. The heating is achieved with nominal supply/return water temperatures of 45°C/35°C with combined floor heating, radiator heating and exhaust air heat recovery. Results indicate that the DH system was able to maintain desired level of comfort in a residential apartment complex. H.I. Tol et al. [14-15] proposed design and optimization approach for piping network of low temperature district heating system. The effects of network type and substation configuration on supply and return pipe dimensions were analyzed using Termis software. Buffer tank for domestic hot water production corresponds to a low heat loss in pipe network. It was also observed that looped DH network bypass approach results in better user comfort and smaller heat loss [16].

Later, D. Rosa et al. [17] has investigated the optimal design of piping network for low energy district heating with a focus on heat loss. Various pipe configurations are considered, including flexible pre-insulated twin pipes with symmetrical or asymmetrical insulation, double pipes, and triple pipes. The largest heat loss reduction was observed for double pipe, 6~12% compared to other pipe configurations. Hongwei Li et al. [18] presented the idea of utilization of return water from DH network and further utilized it for low temperature district heating using heat pump. The component level analysis of the low temperature DH system is investigated in past such as [19] investigated the effect of heat exchanger for low temperature district heating and conclude that the required heat transfer area is relatively large compare to medium temperature DH system due to low pinch point temperature difference. Olsen et al. [20] concluded that the low-energy DH systems competed well with alternative heating systems in the socioeconomic point of view, in which low temperature operation was obtained by means of using substations with an adequate control philosophy adopted in each building. A number of studies have already discussed various methods for the heat loss reduction from the primary and secondary distribution network. Demand side management coupled with dynamic energy storage can fairly reduce the peak load periods [21]. A practical example of eliminating the use of fossil fuels in peak hours is illustrated in the Jyväskylä district heating system in Finland [22]. It has been observed that lower capital cost and higher electricity price made the cogeneration system economical viable option for district heating in Nordic countries [23]. A comprehensive and detailed economic analysis of the district heating system has been conducted by Persson and Werner [24]. They include the heat loss and pressure drop loss in the operating cost of DH system and carried an economic assessment based on payback period. In the studies of Mehment Tan et al. [25], a thermodynamic and economic evaluation of a geothermal district heating system was performed in the advanced exergetic and exergoeconomic analysis compared to conventional method.

In their study, the exergy destruction and the total operating cost within each component of the system were split into endogenous/exogenous and unavoidable/avoidable parts. The results showed that exergetic efficiency and the exergy economic factors of the overall system for the Saraykoy GDHS were determined to be 43.72% and 5.25% according to the conventional tools and 45.06% and 12.98% according to the advanced methods. A number of DH network configurations have been considered and optimized based on the economic assessment and environmental factors [26].

The published works primarily focused on design and optimization of low temperature district heating system based on the fixed supply and return temperatures, methods to reduce the heat loss and control strategies to maintain desired temperature levels. Few studies have investigated the impact of supply temperature on individual components of the low temperature DH system, such as [19]. But, the effect of the variation in supply temperature and return temperature on the overall low temperature DH system has not been reported yet. The justification of yet another paper on the topic is that it is of crucial importance to find the optimum supply temperature and return temperature for a low temperature DH system. The supply and return temperature influence the selection and design of all equipment like, the pumps, piping network and heat exchangers. Change in these crucial components will result in variation of capital and operating cost of the project. This study will help to choose the optimum supply and return temperature for the low temperature DH system based on techno-economic evaluation of the system as a whole by considering the impact at equipment level. The results will support to reduce the operational cost and the investment cost of the low temperature DH system

The present study aims to investigate the effect of the supply and return temperature on the heat loss, pumping power and area of domestic hot water heat exchanger unit. The optimization study will be performed to find the optimum range of supply temperature and temperature difference under local condition of South Korea for a typical residential apartment complex. There exists a trade-off between heat loss cost, pumping power cost and cost of the domestic hot water heat exchanger unit so the optimization will be performed to find the suitable design supply temperature and temperature difference. Economic analysis will be performed to analyze and estimate the optimum design supply temperature and temperature difference in the secondary network of a low temperature DH system.

Design of Low Temperature DH Network

This study primarily focuses on the design optimization of secondary distribution network of a low temperature DH system. The secondary distribution network of a low temperature district heating system consist of secondary pipe network (supply and return pipe network) and domestic hot water connection which includes space heating and domestic hot water heat exchanger unit.

Pipe Network

The pipe design for the secondary distribution network is based on the velocity restriction. The recommended velocity of hot water in the district heating network is restricted to 2 m/s [27]. The building heating load is estimated in simulation environment of TRNSYS software [28] based on the weather data, occupancy, building envelop, and building material. For each value of supply temperature and temperature difference, the corresponding flow rate of hot water is estimated. The maximum value of flow rate over the year is chosen for the design of secondary pipe network. The PEX (Cross-linked polyethylene) pipes are selected for underground (from substation to building basement) and STS pipe (Carbon steel pipe for high pressure) selected for pipe connection inside the building (from basement to floor 1~15). The properties of PEX and STS pipes are shown in the Table 2.

Table 2: Properties of secondary pipe network for low temperature district heating [29]

Pipe	Thermal conductivity [W/m·K]	Insulation thickness [mm]	Insulation heat conductivity [W/m·K]
PEX	64	40	0.0348
STS	16.2	28.9~36.9	0.0234

Twin pipes are used from the substation to the building basement and the pipe length is 197m. The vertical pipes in the building are designed based on velocity restriction of 2m/s [27] to avoid the water noise in the apartment complex. The supply and return pipes are further divided into four sections. The diameter of supply and return pipe changes along the vertical length of the building due to gradual decrease of the mass flow rate of hot water. The detailed layout of the secondary pipe network is shown in Figure 2.

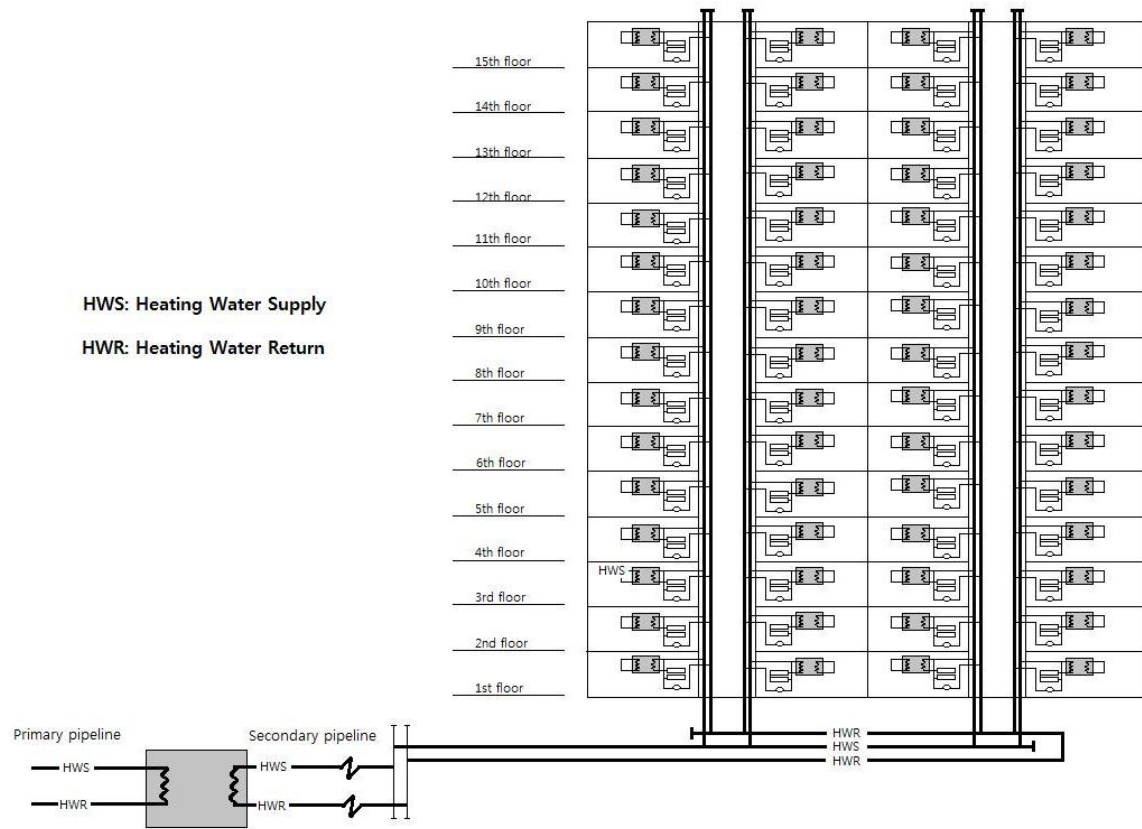


Figure2: Secondary pipe network for low temperature district heating

The pipe dimensions, diameter and corresponding insulation thickness for secondary network of low temperature district heating network are shown in Table 3.

Table 3: Pipe Network Length, Diameter and Insulation for Secondary Pipe Network

Pipe		Diameter [mm]	Total Length [mm]	Insulation Thickness [mm]
Underground	Underground	80.00	19,740	50
Basement Vertical	Supply Line	80.00	4,260	50
	Return Line	80.00	8,500	50
	01~02 Floor	65.65	560	40
	03~08 Floor	50.50	1,680	40
	09~11 Floor	40.40	830	40
	12~15 Floor	32.32	1,110	40

Space Heating

The space heating is conventional floor heating system and direct connection for floor heating is adopted for simulation which is parallel to domestic hot water unit. The layout of the floor direct floor heating concept is shown in Figure 3. The thermostatic valve in the floor heating compares the supply and return temperature from floor heating to maintain the supply temperature at the desired level. It does not only reduce the heat loss but also ensures the instant user comfort.

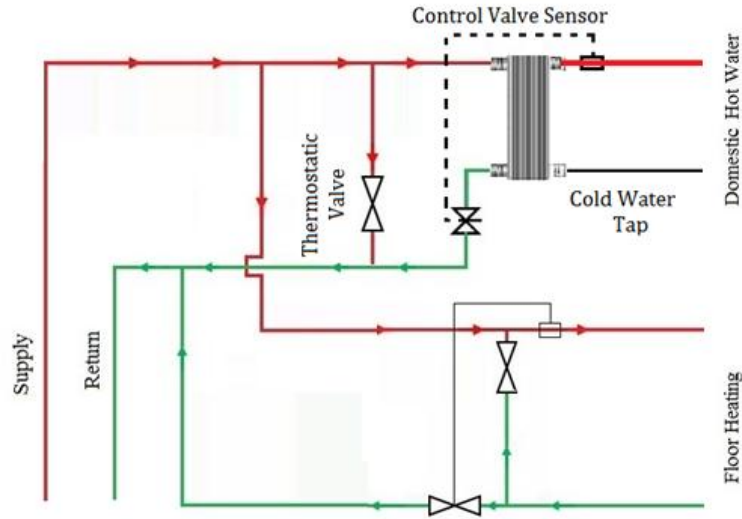


Figure 3: Space heating layout for a low temperature district heating system

Domestic Hot Water

Brazed plate heat exchanger is used as domestic hot water heat exchanger unit due to its compact size. The geometry of the plate heat exchanger is shown in Figure 4.

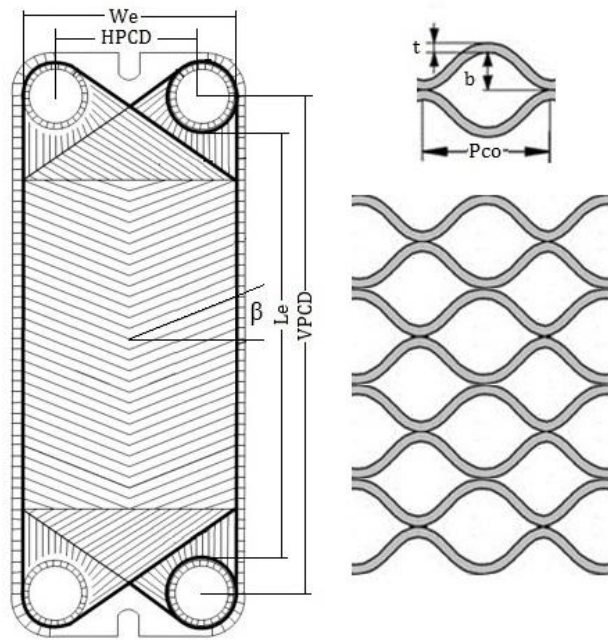


Figure 4: Geometry of plate heat exchanger used in domestic hot water unit

The design of plate heat exchanger is based on log mean temperature difference method. The heat transfer coefficient of water in plate heat exchanger is calculated by

$$Nu_w = \frac{\alpha_w D_h}{k} = 0.724 \left(\frac{6\beta}{\pi} \right)^{0.646} Re^{0.583} Pr^{0.33} \quad (1)$$

The design of heat exchanger is discussed in detail in our previous work [30] and the same approach was adopted for the design of domestic hot water heat exchanger. The in-house unit of domestic hot water unit consists of an instantaneous heat exchanger unit. When the cold water tap is opened, the sensor opens the control valve and supply water flow through the heat exchanger by comparing the set hot water temperature. The set hot water temperature is 40°C in the present study. A thermostatic sensor has been used to keep the secondary line warm and so that the user can instantly access the hot water. The set temperature of the thermostatic sensor is 35°C. The detailed layout of the internal heat exchanger unit is shown in Figure 3.

Building Model

The building is one of the residential apartment complexes in Hankang Town of Seoul city in South Korea. The building is multistory residential building with 15 floors, 4 apartments on each floor and total number of households are 60. The floor heating area of each floor is 85m². Floor plan of household unit and apartment complex is shown in Figure 5.

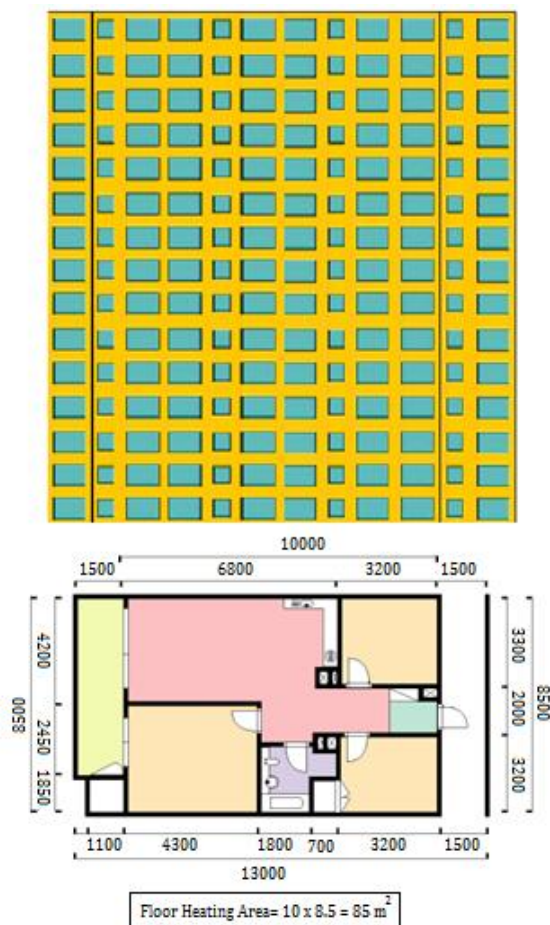


Figure 5: Building model in TRNSYS, floor plan of single household unit, and actual residential apartment complex

Also, wall type and building material properties are shown in table 4 in order to calculate building heating load. The external wall means an exterior wall connected to the ambient environment. External roof means the roof connected to the ambient environment, which is the roof of top floor houses. Ground floor is the ground wall of the first floor that connected the house to the earth. Adjacent wall is the wall between two houses or walls in one house between two rooms. All parameters of each wall are shown in Table 4. Building materials include mortar, brick, insulation and concrete.

Table 4: Properties of the building material of residential apartment complex

Wall	Layer	Layer thickness [m]	Wall thickness [m]	U-value [W/m ² ·K]	Solar absorptance of wall	Long wave emission coefficient
External Wall	Mortar	0.018	0.428	0.248	0.6	0.9
	Brick	0.090				
	Insulation	0.050				
	Concrete	0.200				
External Roof	Insulation	0.070	0.220	2.202	0.6	0.9
	Plywood	0.002				
	Concrete	0.200				
Ground floor	Concrete	0.200	0.230	1.941	0.6	0.9
	Timber Floor	0.030				
Adjacent	Mortar	0.018	0.086	3.802	0.6	0.9
	Brick	0.050				
	Mortar	0.018				

Building properties include total thickness, U-value, solar absorptance and long wave emission coefficient. U-value is the overall heat transfer coefficient and measures how well a wall transfer heat. Solar absorptance specifies, as a decimal fraction, the solar radiation absorptance of an exterior surface of an external wall or roof. Long wave emission coefficient is the heat transfer coefficient of the long wave radiation between two walls or wall and windows. Detailed layer data is presented in Table 5.

Table 5: Thermal properties of the wall material of the building

Unit Material	Layer Thickness [m]	Thermal Conductivity [kJ/h·m·K]	Density [kg/m ³]	Specific Heat Capacity [kJ/kg.K]
Mortar	0.018	5.45	2,000	0.80
Brick	0.090	2.60	1,800	0.80
Insulation	0.050	0.12	40	1.47
Concrete	0.200	5.50	2,300	0.90
Insulation	0.070	0.12	40	1.47

For heating load calculation, following assumptions have been made during heating load calculation in the simulation environment of TRNSYS.

- Floor heating system only works during winter season, which is from November to April. During summer season, district heating system mainly used to supply domestic hot water.
- Heating system will turn on when the room air temperature falls below than 15°C.
- Infiltration rate is assumed 0.6 per hour and occupancy of 4 peoples in each apartment is considered.
- Weather data of Seoul is used from TRNSYS database for the simulation and estimation of heating load.
- Domestic hot water usage is 75~150 liters per person per day [27].

Simulation and System Modeling

Google sketch up and TRNSYS have been used for simulation and optimization. Google sketch up, a 3D modeling tool, is used for architecture, civil and mechanical model of the building. TRNSYS is used to simulate the transient behavior of the apartment complex and total heating load is estimated for giving supply temperature and temperature difference. The detailed layout of the optimization process is shown in Figure 6, while the schematic diagram of secondary pipeline of 2 pipe district heating system in TRNSYS is shown in Figure 7.

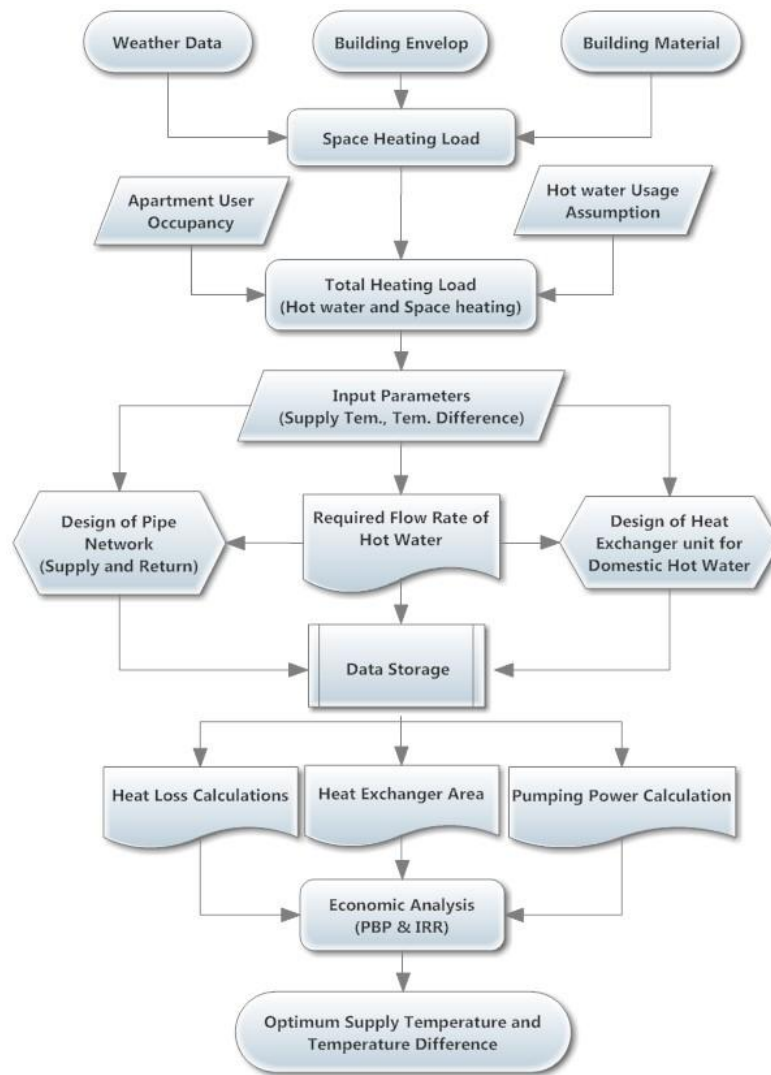


Figure 6: Detail flow chart of the simulation of low temperature district heating

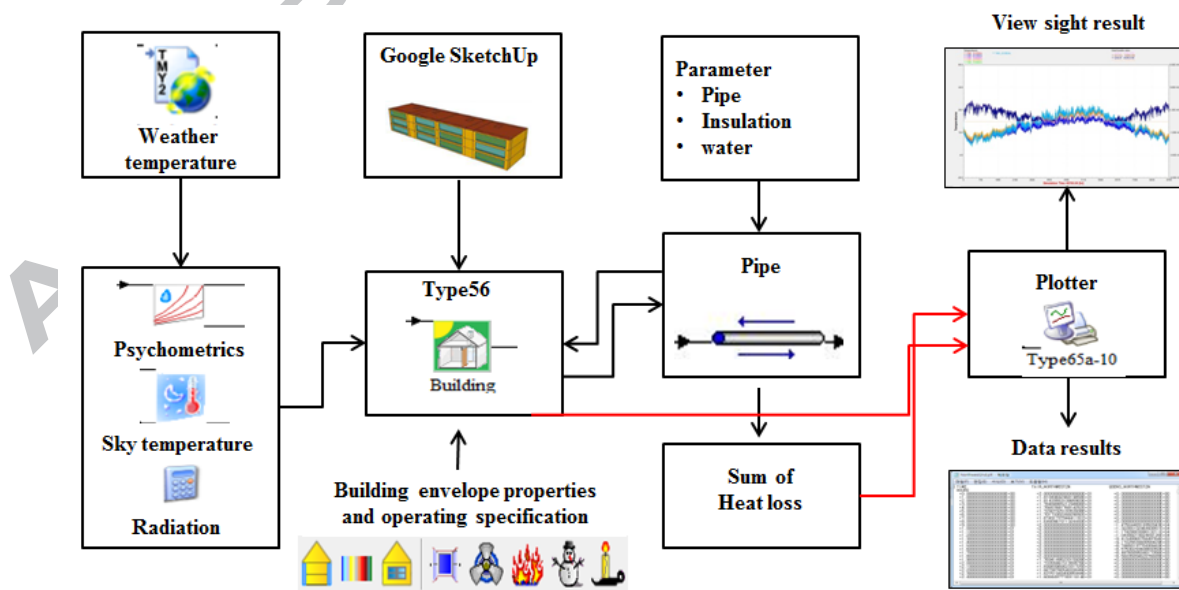


Figure 7: Schematic diagram of secondary district heating system in TRNSYS

It presents the logical relationship used in the simulation. In the first step, building model is developed in Google sketch up. In the next step, the building model is imported into TRNBuild, building parameters and space heat requirements are defined, and then weather data are used to calculate hourly building heating demand. In order to study the influence of supply temperature and return temperature on the low temperature district heating system, simulation model is imported in TRNSYS. Figure 8 shows a schematic of the secondary distribution network model. This model is a detailed secondary pipeline network from substation to individual consumer households.

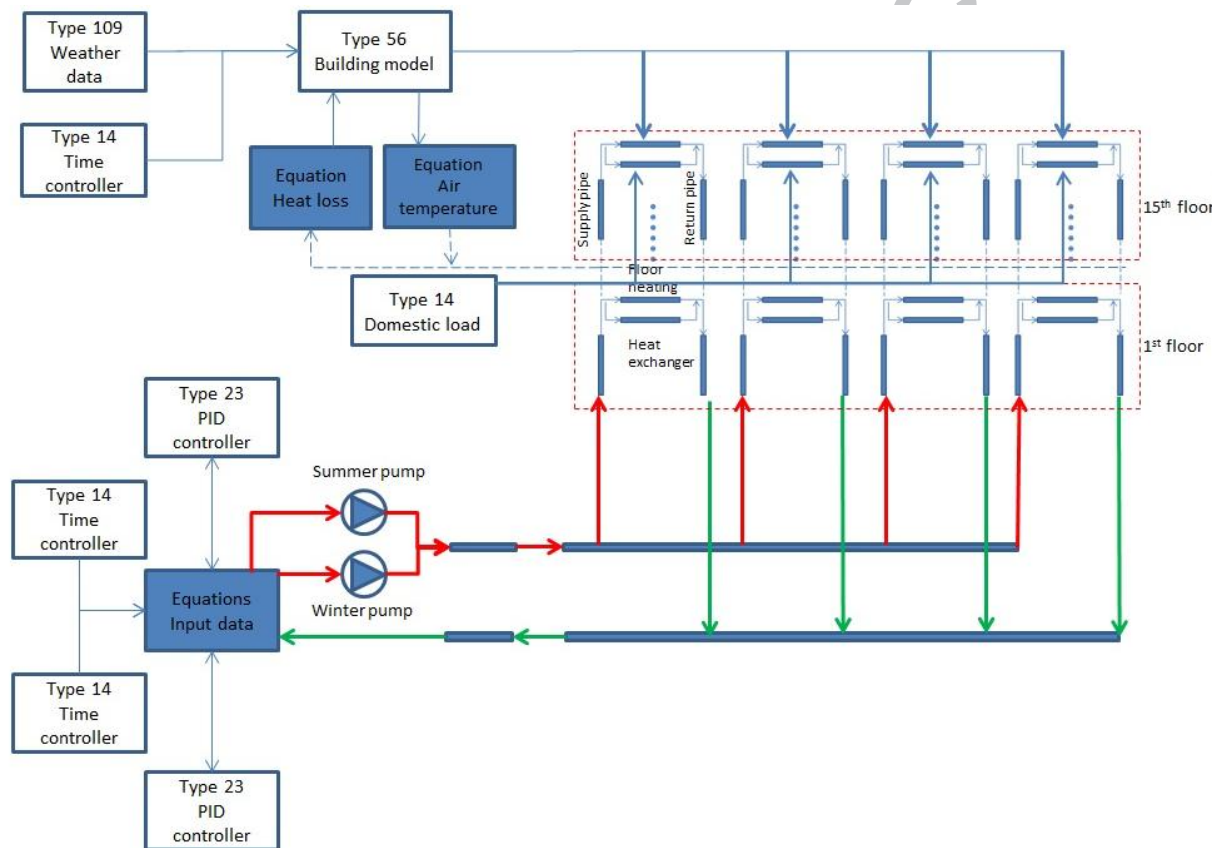


Figure 8: TRNSYS simulation model for optimization of secondary district heating system

Heat Loss

The heat loss from an insulated pipe consists of convective heat transfer from the fluid surface to pipe, conduction heat transfer from carrier pipe, the conduction heat transfer from the insulation, conduction heat loss from the pipe casing, and finally the convective heat loss from the pipe surface to the outside environment. The heat loss is affected by the ambient temperature, fluid mean temperature inside pipe, pipe dimensions, insulation and flow rate of fluid. The heat loss modeling form an insulated DH pipe is shown in the Figure 9.

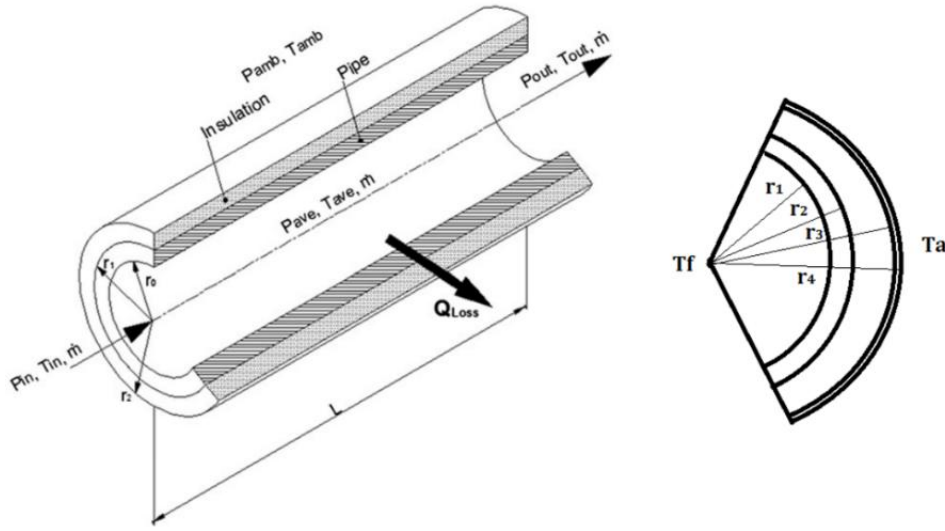


Figure 9: Heat loss from insulated district heating pipe [31]

The heat loss from each part decreases along the radius, and the overall heat loss from the insulated pipe is

$$Q_{loss} = UA_{p,s}(T_f - T_a) = UA_{p,s}\Delta T \quad (2)$$

Whereas U is overall heat transfer coefficient given by

$$U = \frac{1}{R}; \quad R = \frac{1}{h_i} + \frac{r_4 \ln \frac{r_2}{r_1}}{k_p} + \frac{r_4 \ln \frac{r_3}{r_2}}{k_p} + \frac{r_4 \ln \frac{r_4}{r_3}}{k_c} + \frac{1}{h_o} \quad (3)$$

The heat transfer coefficient inside the pipe is estimated by [31]

$$h_i = \frac{k_p}{D_1} \times 0.023 Re^{0.8} Pr^{0.4} \quad (4)$$

The outside air heat transfer coefficient is estimated [31]

$$h_o = 13.79 + 0.03232\Delta T - 40.86D_4 + 0.000117\Delta T^2 + 97.3D_4^2 - 0.01388\Delta TD_4 \quad (5)$$

For heat loss calculations, the properties of pipe are shown in Table 6.

Table 6: Properties of the insulated district heating pipe [29]

Pipes	Density [kg/m ³]	Thermal conductivity [W/m.K]	Thermal capacity [kJ/kg.K]
Carrier pipe	940	0.38	2.31
Insulation	60	0.0237	1.21
Outer pipe	918	0.33	2.31

Pressure Drop

Pumping power is the power consumed to overcome the system pressure loss, to ensure that every house can be supported with required load of hot water and space heating. Three types of pressure losses have been considered in the present study including, frictional pressure drop, fittings pressure drop, pressure drop due

to sudden expansion and contraction. The power absorbed by the pump in kW at a certain rotational speed is given by [32]

$$P = \frac{\gamma \times V_{fr} \times H_p}{1000 \times \eta_p} = 3600 \times w_p \times V_{fr} \quad (6)$$

$$w_p = 0.00272 \times \frac{H_p}{\eta_p}$$

Where γ is specific weight of water, V_{fr} is volume flow rate of water in m^3/s , H_p is the pump head at specific operating speed in m, η_p is the efficiency of the pump, w_p is specific pumping power in kWh/m^3 .

Economic Assessment

The economic feasibility of the low temperature district heating was analyzed by on the basis of payback period and internal rate of return. The discounted payback approach has been adopted to calculate the payback period, given by

$$PaybackPeriod = PBP = \ln \left(\frac{1}{1 - \frac{IC \times r}{CF}} \right) \div \ln(1 + r) \quad (7)$$

Whereas, IC=Initial investment cost (outflow), r=discount rate (5.25% in present study) and CF=Periodic Cash flow. The internal rate of return is given by

$$\left[\left(\frac{CF_1}{(1+r)^1} \right) + \left(\frac{CF_2}{(1+r)^2} \right) + \left(\frac{CF_3}{(1+r)^3} \right) + \dots + \left(\frac{CF_n}{(1+r)^n} \right) \right] - IC = 0 \quad (8)$$

Whereas, n is number of years (30 in present study). The secondary distribution pipe network is designed for supply temperature of 65°C and temperature difference of 18°C. The corresponding pipe network cost, heat loss cost, pumping power cost and cost of heat exchanger unit is also calculated. The supply temperature of 65°C and temperature difference of 18°C is taken as base case. The change in heat loss cost, pumping power cost, the heat exchanger cost and pipe network cost due to changes in supply temperature and temperature difference are taken into account in economic analysis. The savings or loss due to heat loss and pumping power are considered as cash flow. The cost of the additional heat exchanger area is considered as investment cost. For change in supply temperature and temperature difference, the additional cost of secondary pipe network is also considered if it is higher than the base case. The details of the pipe network cost and electricity cost are shown in Appendix A. It should be noted that the conversion from USD (\$) to Korean Won (₩) is as; 1\$=1180₩).

Results and Discussion

The heat load of the residential apartment building depends on the user behavior, ambient temperature, building material and building envelop. The heating load of the apartment complex is calculated in the simulation environment of TRNSYS. The simulation results have been compared with the experimental data, for year 2014 for the same building. The simulation results show reasonable agreement with experimental values of the heating load with an average error of $\pm 4.82\%$. The variation of the apartment complex heating load over the year is shown in Figure 10.

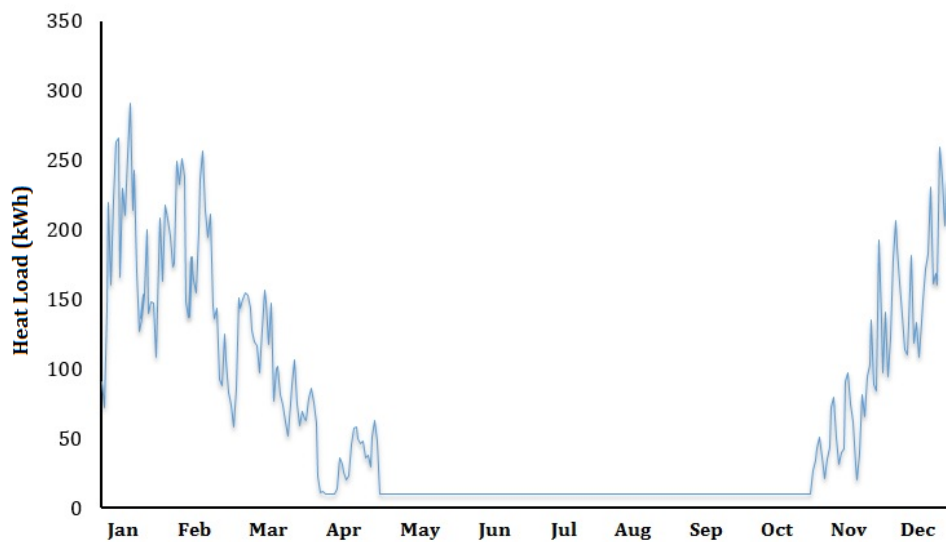


Figure 10: Variation of apartment complex heating load over the year

Due to low ambient temperature in winter (October ~April), the building load is high due to relatively high demand of space heating and hot water. However, during summer period (April~October), the fluctuation in building load is small due to low building heating load requirement. In summer, there is no need of space heating and only hot water is required for household utilization. Therefore, the heating demand in summer is low with very minor fluctuation in heating load. The heating load is controlled by the flow rate of the hot water with the help of a variable frequency drive pump. For each supply temperature, the return temperature is set to a specific value. When the temperature falls below the set value of return temperature, mass flow rate of hot water will be increased by the variable frequency drive pump with the help of a PID control loop. The PID controller is tuned initially, to maintain the return temperature within the range of set value of return temperature. The mass flow rate variation over the year follows the same trend as that of the heating load. The higher the heating load, the higher will be the mass flow rate of hot water. The variation of the mass flow rate of the hot water in the secondary network over the year is shown in Figure 11.

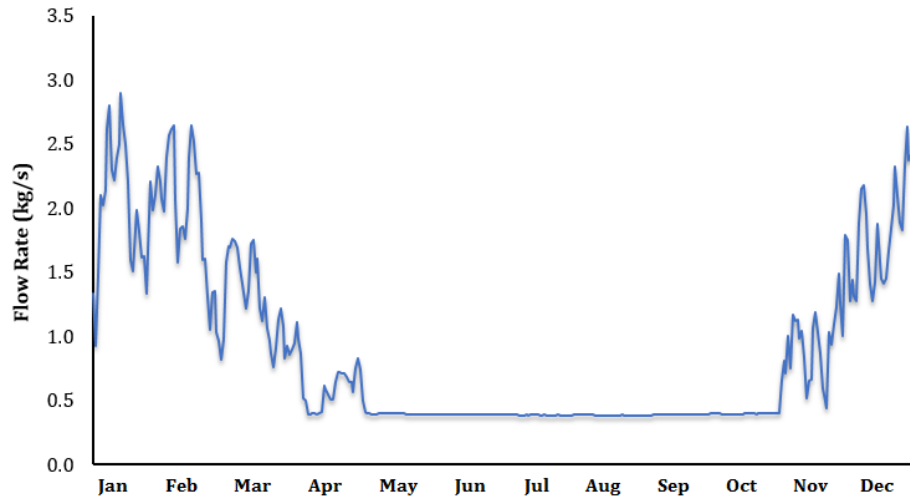


Figure11: Flow rate of supply hot water in secondary network

The mass flow rate of the supply hot water is higher in winter due to higher heating load demand and lower in summer due to lower heating load of the apartment complex. The pumping power in the DH system is directly related to mass flow rate of the supply hot water in the network. An increase in mass flow rate of supply hot water results in an increase in Reynolds number. Due to increase of Reynolds number, the pressure drop in the secondary network also increases. The variation of the pressure drop over the year for supply temperature of 60°C and the temperature difference as 20°C is shown in Figure 12.

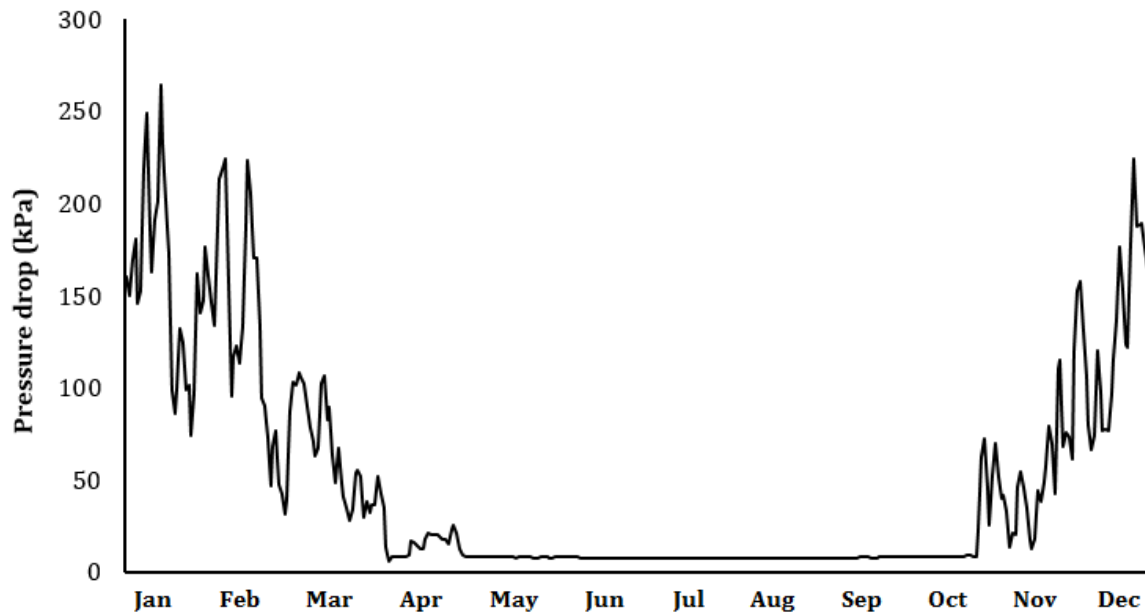


Figure 12: Variation of pressure drop in the secondary network of LTDH system

The pressure drop in the secondary network follows the same trend as that of the mass flow rate of the hot water. The higher the mass flow rate, the higher will be the pumping power.

During the summer season, the pumping power is almost uniform as the space heating is turned off and only domestic hot water is required. Annual pumping power and annual cost of the pumping power for supply temperatures and corresponding temperature difference are shown in Table 7 and Table 8 respectively.

Table 7: Annual pumping power [kWh] for range of supply temperature and temperature difference

Supply Temperature T_s [°C]	Temperature Difference T_D [°C]				
	18°C	20°C	22°C	25°C	27°C
45°C	3,223	2,429	2,428	1,298	1,050
50°C	3,143	2,366	1,813	1,279	1,023
55°C	3,063	2,304	1,766	1,233	998
60°C	2,985	2,244	1,721	1,201	972
65°C	2,908	2,185	1,676	1,171	948

Table 8: Annual pumping power cost [Thousands \$] for range of supply and temperature difference

Supply Temperature T_s [°C]	Temperature Difference T_D [°C]				
	18°C	20°C	22°C	25°C	27°C
45°C	506	380	292	204	165
50°C	520	391	300	209	169
55°C	533	401	308	215	174
60°C	547	412	316	223	178
65°C	561	423	423	226	183

At lower supply temperatures, the mass flow rates are relatively higher to maintain the desired heating demand. Therefore, pumping power is higher at lower supply temperature and lower at higher supply temperatures. Temperature difference also affects the pumping power. At higher temperature difference, the mass flow rate of hot water is lower and thus pumping power is relatively lower. The pumping power increases with temperature difference increasing. The variation of the area of domestic hot water heat exchanger with the supply temperature is shown in Figure 13. The consumer required temperature was set at 40°C and an average temperature of city water is taken as 15°C. For the lower district heating supply temperature, the pinch point is smaller and results in the larger heat transfer area of domestic hot water heat exchanger. For supply temperature of 45°C, the pinch point is 5°C, and therefore the heat transfer area is the largest among considered range of supply temperatures. It can be concluded that higher the supply temperature is, the lower will be the heat exchanger area. Moreover, temperature differences also play a critical role in the heat exchanger area.

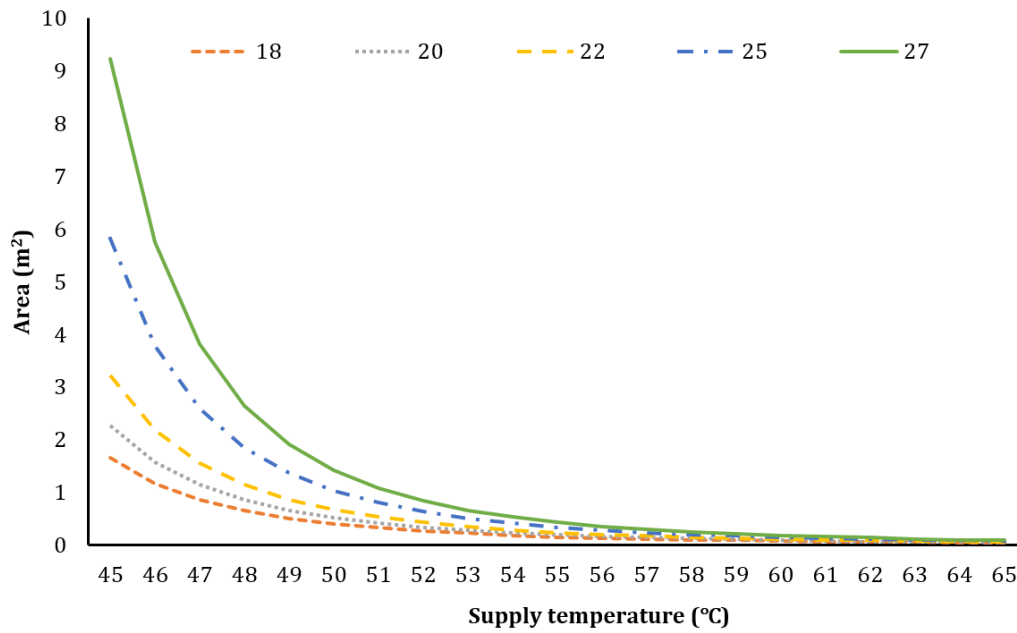


Figure 13: Heat exchanger area for range of supply temperature and temperature difference

The higher temperature difference leads to an increase in the heat exchanger area. The temperature difference of 27°C leads to the highest heat transfer area of the heat exchanger. It is observed that the heat exchanger area is less than 1m² when the supply temperature is above than 50°C. The effect of temperature difference is more visible for supply temperature lower than 50°C. The cost of plate heat exchanger is estimated based on the quotation that have been obtained from the local Korean Market. The empirical correlations have been developed considering the heat exchanger area as the prime factor. The cost correlation is given by

$$Cost[Krw] = 204944.81A_{hx} - 7355.7276A_{hx}^2 + 392.9A_{hx}^3 \quad (6)$$

The cost of the heat exchanger for a range of supply temperature and temperature difference is shown in Table 9.

Table 9: Heat exchanger cost [Thousands ₩] for range of supply temperature and temperature difference

Supply Temperature	Temperature Difference				
T_s [°C]	T_d [°C]				
	18°C	20°C	22°C	25°C	27°C
45°C	18,849	32,434	41,423	57,822	83,897
50°C	7,725	8,714	10,197	14,152	17,922
55°C	2,472	2,963	3,852	6,236	8,034
60°C	1,739	1,832	1,894	2,169	2,957
65°C	1,483	1,545	1,607	1,730	1,892

The cost of heat exchanger increases with increase in temperature difference, and decreases with the increase in supply temperature. The heat loss from the secondary network consists of two parts, heat loss from the supply line and return line. The supply and return pipes from the substation to the apartment are underground. The heat loss varies over the year depending on the ambient temperature and customer heat load as shown in Figure14.

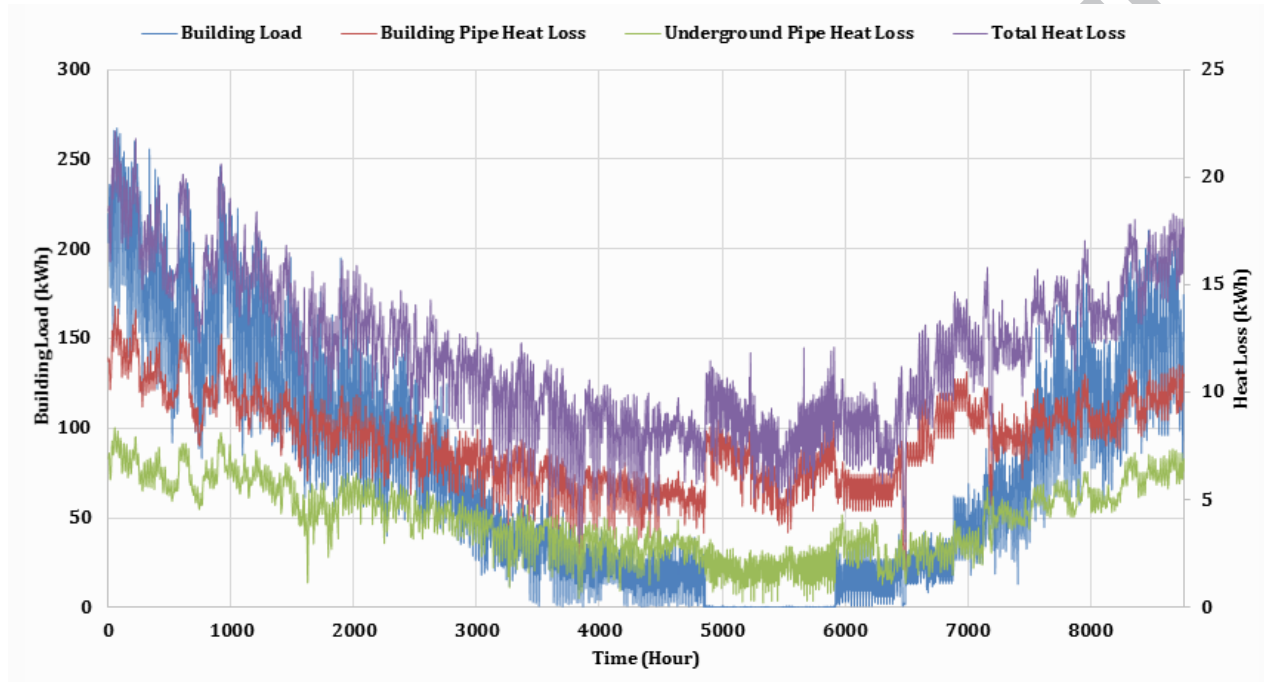


Figure 14: Variation of heat loss from secondary network over the year

Average annual heat loss relative to total heat supplied for each supply temperature for temperature difference of 20°C is shown in the Figure 15.

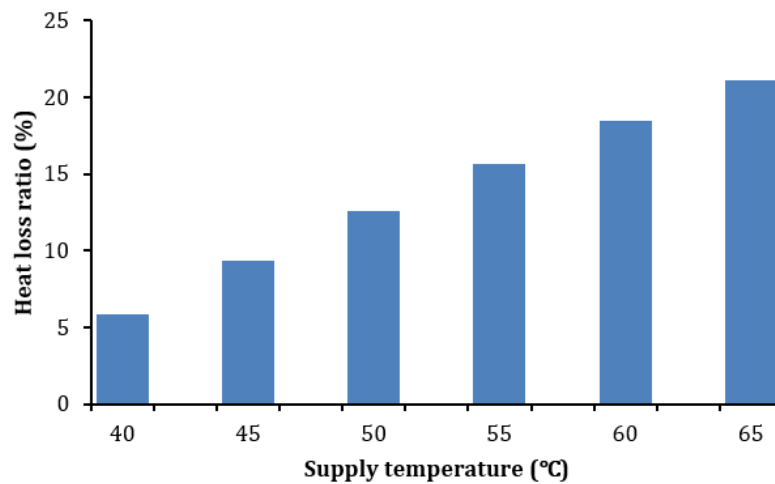


Figure 15: Relative Percentage of heat loss to heat supplied for range of supply temperatures

The heat loss is maximum for the higher supply temperature and lower for low supply temperatures. The highest heat loss occurs when the supply temperature is 65°C and minimum when the supply temperature is 40°C. The relative distribution of heat loss cost for each section of the secondary pipe network is shown in Figure 16. The underground supply pipeline represents 34% of total heat loss cost which is the highest heat loss cost compared to other pipe portions.

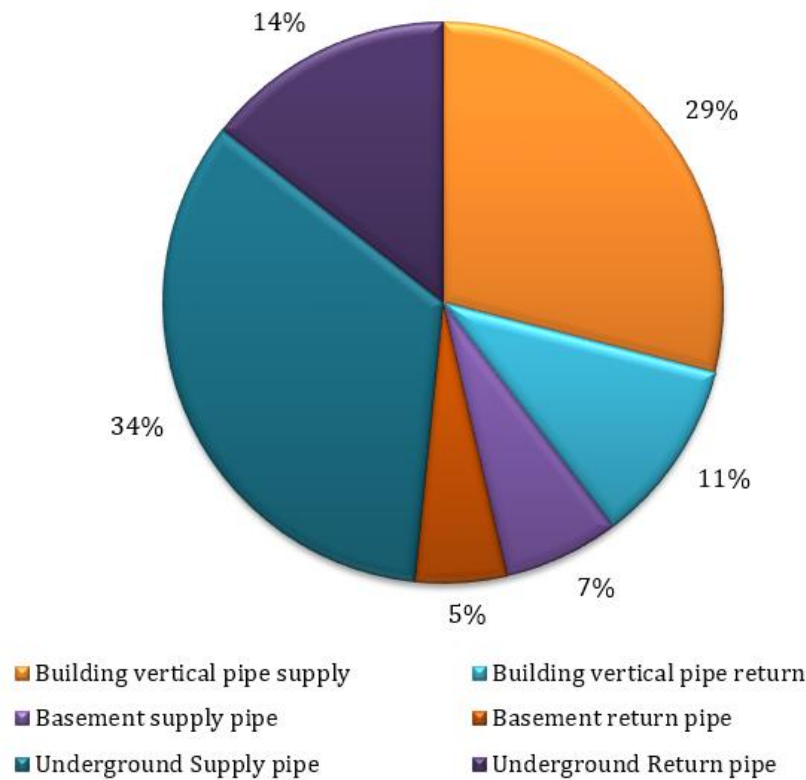


Figure 16: Relative distribution of heat loss in secondary network distribution

This is because water supply temperature in supply pipe is much higher than return temperature, and the ambient temperature is quite low. The second biggest part of heat loss comes from underground return pipe. This presents, even the return temperature increased, but due to high temperature difference between return hot water and ambient temperature, the heat loss of this part is still higher than other parts. Pipe heat loss from the vertical supply and return pipe are 14% and 11% respectively. Due to shorter length of basement supply and return pipe, heat loss for basement supply and return pipe is only 7% and 5%. This is because there are four lines of vertical pipes in this building. Each line, the pipe length is 42m, in total; the pipe length is 168m, which has a much bigger surface area. With high surface area, the heat loss through the pipe surface is large enough. The heat loss cost variation with the supply temperature and temperature difference is shown in Table 10.

Table 10: Heat loss cost [Thousands ₩] for range of supply temperature and temperature difference

Supply Temperature T_s [°C]	Temperature Difference T_d [°C]				
	18°C	20°C	22°C	25°C	27°C
45°C	3,556	3,311	3,062	2,694	2,432
50°C	4,703	4,460	4,213	3,844	3,587
55°C	5,848	5,607	5,362	4,992	4,737
60°C	6,993	6,753	6,509	6,140	5,887
65°C	8,138	7,898	7,655	7,287	7,035

The economic feasibility of the low temperature district heating is analyzed by economic analysis considering payback period and internal rate of return as major decision factors. Heat loss is minimum and pumping power is maximum at supply temperature of 65°C and temperature difference of 18°C. Therefore, when the supply temperature decreases and temperature difference increases, more heat loss saving is possible with small plenty of additional pumping power. Similarly, heat exchanger cost is also minimum at supply temperature of 65°C and temperature difference of 18°C. The reason for minimum cost is that at 65°C supply temperature and temperature difference of 18°C, the pinch point temperature difference in domestic hot water heat exchanger will be relatively large. Therefore, the supply temperature of 65°C and temperature difference of 18°C is taken as the base case in the present study. When the supply temperature is further lowered from 65°C, the net cost of heat loss and pumping power is considered as net saving or profit. Similarly, when the supply temperature is lowered from 65°C, the additional increase in the heat exchanger area is considered as an investment cost. Payback period and internal rate of return are chosen as economic analysis parameters with project life of 30 years. The results of economic analysis are shown in Figure 17 and 18 respectively. The results of payback period are shown in Fig. 17. At lower temperature, the investment cost dominates over the savings. It is observed that the payback period is lowest for the supply temperature 60°C and maximum for supply temperature of 45°C. The temperature difference also affects the payback period, the minimum payback period is observed for temperature difference of 18°C and maximum for temperature difference of 27°C. However, this is true for supply temperature of 45~55°C. For supply temperature of 60°C and 65°C, the highest payback period corresponds to temperature difference of 18°C and minimum at temperature difference of 27°C.

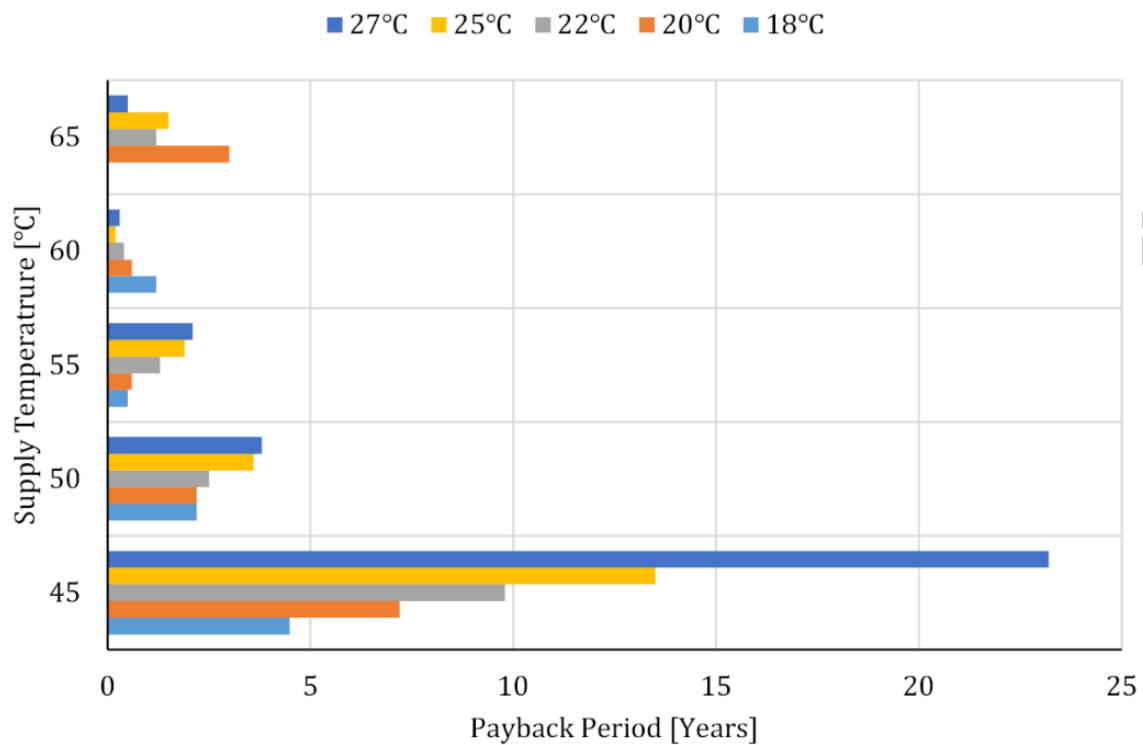


Figure 17: Payback period for range of supply temperature and temperature difference

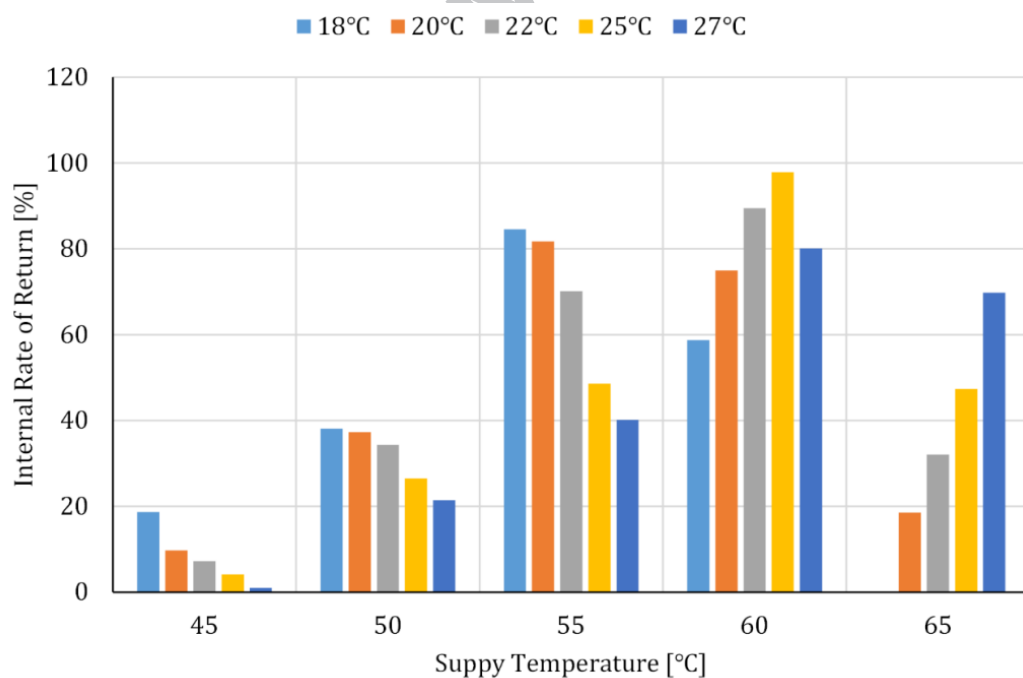


Figure 18: Internal rate of return for range of supply temperature and temperature difference

This is because at lower temperature difference, the savings are dominated and at higher temperature difference investment cost is dominated over the savings. The internal rate of return, on the other hand, gives better insight to the project economics. The effect of supply temperature and temperature difference on internal rate of return is shown in Fig.18.

For the low supply temperature of 45°C and 50°C, the internal rate of return is very small compare to the supply temperature of 55°C and 60°C. For the lower supply temperature, although the savings from the heat loss is higher, but the corresponding cost of domestic hot water heat exchanger is very large which overcomes the savings. The supply temperature of 55°C and 60°C provide the highest internal rate of return and perfectly balance the investment cost and savings. The temperature difference also affects the internal rate of return. Except 60°C, the trend of temperature difference with internal rate of return is similar, i.e. internal rate of return decreases with decrease in temperature difference. However, in case of 60°C the internal rate of return is highest for temperature difference of 25°C.

Conclusion

Secondary distribution network of the low temperature district heating system is optimized within the logical bound of supply and return temperature. The supply and return temperature directly affects the heat loss, pumping power, and the cost of domestic hot water heat exchanger unit. From the results of this study, it can be concluded that

1. There exists an optimum supply and return temperature at which the heat loss saving, pumping power cost and additional cost of heat exchanger unit balance each other in such a way that the net operating cost of the low temperature DH system is minimized.
2. For higher supply temperatures, the heat loss cost dominates over cost of pumping power and cost of heat exchanger unit. At lower supply temperature, the cost of heat exchanger units dominates over the saving of heat loss cost. Based on the economic analysis, the supply temperature of 55°C and 60°C are the optimum supply temperature for the low temperature district heating system under consideration.
3. The optimum temperature difference for supply temperature of 55°C is 18°C, which corresponds to return temperature of 37 °C. Similarly, for supply temperature of 60 °C, the optimum temperature difference is 25°C, which corresponds to return temperature of 35°C.
4. If the supply temperature is further lowered from 55°C, the cost of pumping power and domestic hot water heat exchanger increase significantly. The low supply temperature is also restricted by the Legionella bacteria and as a rule of thumb the supply temperature should be kept above 50°C.

Acknowledgement

This work was partly conducted under the framework of research and development program of Korea Institute of Energy Research (B7-2413-03) and partly supported by KDHC (B6-5513).

References

- [1] Lund, H., Möller, B., Mathiesen, B. V., & Dyrelund, A. (2010). The role of district heating in future renewable energy systems. *Energy*, 35(3), 1381-1390.
- [2] Möller, B., & Lund, H. (2010). Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. *Applied Energy*, 87(6), 1846-1857.
- [3] Lund, H., Hvelplund, F., Kass, I., Dukalskis, E., & Blumberga, D. (1999). District heating and market economy in Latvia. *Energy*, 24(7), 549-559.
- [4] Gustavsson, L., & Karlsson, Å. (2003). Heating detached houses in urban areas. *Energy*, 28(8), 851-875.
- [5] Kelly, S., & Pollitt, M. (2010). An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom. *Energy Policy*, 38(1), 6936-6945.
- [6] Eriksson, O., Finnveden, G., Ekvall, T., & Björklund, A. (2007). Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass-and natural gas combustion. *Energy policy*, 35(2), 1346-1362.
- [7] Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy*, 68, 1-11.
- [8] Wiltshire, R. (2011, October). Low temperature district energy systems. In *Proceedings of the Urban Energy Conference* (pp. 1-13).
- [9] Olsen, P. K., Lambertsen, H., Hummelshøj, R., Bøhm, B., Christiansen, C. H., Svendsen, S., ...& Worm, J. (2008, August). A new low-temperature district heating system for low-energy buildings. In *Proceedings of the 11th International Symposium on District Heating and Cooling*, Iceland.
- [10] A. Dalla Rosa, The development of a new district heating concept. Network design and optimization for integrating energy conservation and renewable energy use in energy sustainable communities, PhD thesis; Technical University of Denmark, 2012.
- [11] Persson, U., Ruehling, K., Felsmann, C., Crane, M., Burzynski, R., Wiltshire, R., & Bevilacqua, C. (2014). Toward 4th Generation District Heating: Experience and Potential of Low-Temperature District Heating.
- [12] Yao, Y., Lian, Z., Liu, W., Hou, Z., & Wu, M. (2007). Evaluation program for the energy-saving of variable-air-volume systems. *Energy and Buildings*, 39(5), 558-568.

- [13] Hasan, A., Kurnitski, J., & Jokiranta, K. (2009). A combined low temperature water heating system consisting of radiators and floor heating. *Energy and Buildings*, 41(5), 470-479.
- [14] Tol, H. I., & Svendsen, S. (2012). Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark. *Energy*, 38(1), 276-290.
- [15] Tol, H. I., & Svendsen, S. (2011, December). Determination of optimum network layout for low-energy district heating systems with different substation types. In *The Third International Renewable Energy Congress (IREC 2011)*, Dec (pp. 20-22).
- [16] Brand, M., Thorsen, J. E., & Svendsen, S. (2012). Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes. *Energy*, 41(1), 392-400.
- [17] Dalla Rosa, A., Li, H., & Svendsen, S. (2011). Method for optimal design of pipes for low-energy district heating, with focus on heat losses. *Energy*, 36(5), 2407-2418.
- [18] Li, H., Dalla Rosa, A., & Svendsen, S. (2010). Design of a low temperature district heating network with supply recirculation. In *12th International Symposium on District Heating and Cooling*.
- [19] Paulsen, O., Fan, J., Furbo, S., & Thorsen, J. E. (2008, August). Consumer unit for low energy district heating net. In *The 11th International Symposium on district heating and cooling*.
- [20] Olsen, P. K., H. Lambertsen, R. Hummelshøj, B. Bøhm, C. H. Christiansen, S. Svendsen, C. T. Larsen, and J. Worm. (2008, August). A new low-temperature district heating system for low-energy buildings. In *Proceedings of the 11th International Symposium on District Heating and Cooling, Iceland*.
- [21] Wigbels, M., Bohm, B., & Sipila, K. (2005). Dynamic heat storage and demand side management strategies. *EUROHEAT AND POWER-ENGLISH EDITION*-, 11, 58
- [22] Kärkkäinen, Seppo, Kari Sipilä, Lauri Pirvola, Juha Esterinen, Esko Eriksson, Sakari Soikkeli, Marjukka Nuutinen, Heikki Aarnio, Frieder Schmitt, and Claus Eisgruber. (2003). Demand side management of the district heating systems. *VTI Research Notes*, 2247.
- [23] Keppo, I., & Savola, T. (2007). Economic appraisal of small biofuel fired CHP plants. *Energy conversion and management*, 48(4), 1212-1221.
- [24] Persson, U., & Werner, S. (2011). Heat distribution and the future competitiveness of district heating. *Applied Energy*, 88(3), 568-576.
- [25] Tan, M., & Keçebaş, A. (2014). Thermodynamic and economic evaluations of a geothermal district heating system using advanced exergy-based methods. *Energy Conversion and Management*, 77, 504-513.
- [26] Curti, V., von Spakovsky, M. R., & Favrat, D. (2000). An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: Methodology. *International Journal of Thermal Sciences*, 39(7), 721-730.

- [27] Public housing complex plat-based guide, 2008, Korea Engineering & Consulting Association.
- [28] Beckmann, W. A. (1988). A Transient System Simulation Program Solar Energy Lab. Madison Wisconsin.
- [29] Pipe size and capacitance, <http://www.pipeteckorea.co.kr/>, Accessed on 28 February 2015
- [30] Imran, M., Usman, M., Park, B. S., Kim, H. J., & Lee, D. H. (2015). Multi-objective optimization of evaporator of organic Rankine cycle (ORC) for low temperature geothermal heat source. *Applied Thermal Engineering*, 80, 1-9.
- [31] Ali Keçebaş, Mehmet Ali Alkan, Mustafa Bayhan, Thermo-economic analysis of pipe insulation for district heating piping systems, *Applied Thermal Engineering*, 2011; 31, pp. 3929-3937
- [32] Sarbu, I., & Valea, E. S. (2015). Energy savings potential for pumping water in district heating stations. *Sustainability*, 7(5), 5705-5719.

Highlights

- Design and optimization of secondary distribution network of a LDH system
- Effect of supply temperature on heat loss, pumping power & heat exchanger area
- There exists an optimum supply temperature that balance the overall cost
- Optimum supply temperature is 60 °C for LTDH system under consideration
- Optimum temperature difference between supply and return temperature is 20 °C

Table: Capital cost of pipe for primary pipe network

Type	Pipe Standard	Price	Carrier Pipe		Insulation	Casing Pipe	
			Inner	Outer	Thickness	Thickness	Outer Dia.
		¥/m	mm	mm	mm	mm	mm
PEX	150A	253300	154.2	165.2	38.4	4	250
	125A	163800	129.6	139.6	39.1	3.5	225
	100A	124000	104.5	114.3	39.4	3.5	200
	80A	103200	80.1	89.1	32.2	3.2	160
	65A	84300	67.3	76.3	28.7	3.2	140
	50A	67600	52.7	60.5	29.1	3.2	125
	40A	49200	41.2	48.6	27.7	3	110
	32A	38300	35.5	42.7	30.7	3	110
	25A	32990	27.2	34	25.5	2.5	90
	20A	29600	21.4	27.2	28.9	2.5	90

Table: Capital cost of pipe for secondary pipe network

Type	Pipe Standard	Price	Carrier Pipe		Insulation	Casing Pipe	
			Inner	Outer	Thickness	Thickness	Outer Dia.
		¥/m	mm	mm	mm	mm	mm
STS (SCH 10)	100A	83780	114.3	108.2	50	0	158.2
	80A	67730	89.1	83	50	0	133
	65A	51550	76.3	70.2	50	0	120.2
	50A	46040	60.5	54.9	50	0	104.9
	40A	41220	46.8	41.2	50	0	91.2
	32A	36400	42.7	37.1	50	0	87.1
	25A	32250	34	28.4	50	0	78.4
	20A	29600	27.2	23	50	0	73

Table: Price of Heat Supplied to the different Customers

Type	Classification	Tariff
Residential	Charges: 1 m ² area = 52.40 ₺	Fixed Rate: 83.50 ₺ per Mcal Spring and Autumn : 81.82 ₺ per Mcal Summer : 73.63 ₺ per Mcal Winter: 85.93 ₺ per Mcal
Industrial	Charges: 1Mcal/h =396.79 ₺	Fixed Rate: 108.41 ₺ per Mcal Demand within contracted Time: 124.68 ₺ per Mcal Demand outside contracted Time : 102.98 ₺ per Mcal

Table 11: Electricity price for industrial usage

Classification	Demand charge (₺/kW)	Energy charge (₺/kW)			
		Time Period	Summer	Spring/Fall	Winter
High Voltage (A)	Option 1	Off-Peak	61.6	61.6	68.6
		Mid-Peak	114.5	84.1	114.7
		On-Peak	196.6	114.8	172.2
	Option 2	Off-Peak	56.1	56.1	63.1
		Mid-Peak	109.0	78.6	109.2
		On-Peak	191.1	109.3	166.7
	Option 3	Off-Peak	55.2	55.2	62.5
		Mid-Peak	108.4	77.3	108.6
		On-Peak	178.7	101.0	155.5